View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Elsevier - Publisher Connector

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 69 (2015) 1249 – 1258

Energy Procedia

International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2014

Dynamic multi-configuration model of a 145 MWe concentrated solar power plant with the ThermoSysPro library (tower receiver, molten salt storage and steam generator)

B. El Hefni[a]* and R. Soler[b]

[a] EDF R&D, 6 quai Watier, 78401 Chatou Cedex, France (baligh.el-hefni@edf.fr)
[b] EDF R&D, 1 Avenue du Général de Gaulle, 92141 Clamart, France (robert.soler@edf.fr)

Abstract

Molten salt technology represents nowadays the most cost-effective technology for electricity generation for solar power plant.

0D/1D models are useful to check, validate and improve through simulation the energy performances of existing power plants. They are also used to find the best design that meets required economical criteria and the preparation of the acceptance test for commissioning of the power plant.

A dynamic multi-configuration model of a concentrated solar power plant has been developed. The component model is meant to be used for power plant modeling with the ThermoSysPro library developed by EDF and released under open source license. The model is based on momentum and mass/energy conservation equations, as 1-dimensionnal (1D), partial differential equations. The model includes a water/steam cycle (economizer, evaporator, superheater, turbines, aerocondenser, water heaters, pumps, valves, tank, volumes and pipes), molten salt thermal storage system (temperature up to 565ºC with a capacity of 8 hours of electricity production without sunlight) and a cylindrical receiver. The distribution of the heat flux received by the receiver may be calculated by Tonatiuh tool (Ray Tracing tool).

The primary aim of this study was to demonstrate the capability of said model to simulate the operating conditions of a solar power plant, and then the capability of the model to check the manufacturers design and targeted performances.

In order to be able to answer to many different situations, we created some variables in some of the component model enabling to switch itself on or off. So (turbine stage, water heater, …), the same model can simulate several different plant configurations.

* Corresponding author. Tel.: +33130878301; fax: + 33130878120.
E-mail address: baligh.el-hefni@edf.fr

1876-6102 © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.03.160

This model (Modelica model, translate with Dymola) includes all typical configurations, thus enabling its use through a user-friendly Excel interface. With this interface, comparisons between various architectures according to given criteria and constraints are easy, thus helping the user to define the best design. This interface can be used by a non-specialist in modeling. Several transients are simulated, the objectives are: check the performances and the design (sizing of the components) given by the manufacturers, verify and validate by simulation the scenario of large transients and to reduce the uncertainty of the prediction on the yearly electricity production (simulation with yearly DNI).

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG

Keywords: ThermoSysPro ; Modelica ; thermal-hydraulics ; Central Receiver System; solar ; CSP plant ; dynamic modeling

1. Introduction

The limited supply of fossil hydrocarbon resources and the negative impact of CO2 emissions on the global environment dictate the increasing usage of renewable energy sources. Solar thermal power plants are a key technology for electricity generation from renewable energy resources.

Of all the technologies being developed for solar thermal power generation, central receiver systems (CRSs) are able to work at the highest temperatures and to achieve higher efficiencies in electricity production.

The main challenge to deal with this energy is its variability along the day (sunrise, sunset, clouds…). Molten salt technology represents nowadays the most cost-effective technology for electricity generation for stand-alone solar power plants. Thermal energy storage (TES) makes it possible to meet the intermediate load profile, a benefit that has a high value to power utilities.

Central receiver systems (CRSs) use a field of distributed mirrors – heliostats – that individually track the sun and focus the sunlight on the top of a tower by concentrating the sunlight 600–1000 times, they achieve temperatures from 800°C to well over 1000°C. The solar energy is absorbed by a working fluid and then used to generate steam to power a conventional turbine. The receiver system is the door for which the energy passes from the field collector to the thermal electric cycle, it represents therefore, the core of the CRS and its performance directly affects plant production.

Modeling and simulation activities play a key role in the design phase and performance optimization of complex energy processes [1 to 11]. It is also expected that they will play a significant role in the future for power plant maintenance and operation.

0D/1D models are useful to check, validate and improve through simulation the energy performances of existing power plants. They are also used to find the best design that meets required economical criteria and the preparation of the acceptance test for commissioning of the power plant.

The potential of Modelica as a mean to efficiently describe thermodynamic models has been recognized for quite a while [1, 2], and has led to the initiative of developing an EDF library for power plant modeling within the ITEA 2 EUROSYSLIB project.

This library, called ThermoSysPro, aims at providing the most frequently used models of components for the 0D-1D static and dynamic modeling of thermodynamic systems, mainly for power plants, but also for other types of energy systems such as industrial processes, energy conversion systems, buildings etc. It involves disciplines such as thermal-hydraulics, combustion, neutronics and solar radiation (see instance [1 to 8].

The ambition of the library is to cover all the phases of the plant lifecycle, from basic design to plant operation. This includes for instance system design, verification and validation of the instrumentation and control system, system diagnostics and plant monitoring. To that end, the library will be linked in the future to systems engineering via the modeling of systems properties (or requirements), and to the measurements made on the real process via state estimation techniques.

Several test-cases were developed to validate the library in order to cover the full spectrum of potential usages for power plant modeling: static and dynamic models of a biomass plant [3], dynamic models of a concentrated solar power plant [4], dynamic model of steam generators for sodium fast reactor [5], two dynamic models of 1300 MWe nuclear power plants covering the primary and secondary loops, three dynamic models of combined cycle power plants and two dynamics models of pulverized coal power plants (once through).

The present paper focuses on the load/unload cycle of the storage tank, an scenario with a typical operation cycle and real DNI has been simulated he primary goal of this study was to demonstrate the capability of model to simulate the operating conditions of a solar power plant, and to check the manufacturers design and targeted performances.

2. Introduction to the ThermoSysPro library

ThermoSysPro is a generic library for the modeling and simulation of power plants and other kinds of energy systems. ThermoSysPro library is developed by EDF and released under open source license.

2.1. General principles of the library

The library features multi-domain modeling such as thermal-hydraulics (water/steam, synthetic oil, flue-gases and some refrigerants), neutronics, combustion, solar radiation, instrumentation and control.

The foundations of the library are based on the first physical principles: mass, energy, and momentum conservation equations, up-to-date pressure losses and heat exchange correlations, and validated fluid properties functions. The correlations account for the non-linear behaviour of the phenomena of interest. They cover all water/steam phases, oil and all flue gas compositions. The granularity of the modeling may be freely chosen. Some correlations are given by default since they correspond to the most frequent use-cases, but they can be freely modified by the user if needed. This includes the choice of the pressure drop or heat transfer correlations. Special attention is given to the handling of two-phase flow, as two-phase flow is a common phenomenon in power plants. The physics of two-phase flow is complex because of the mass and energy transfer between the two phases and the different flow regimes (bubbles, churn or stratified flow…) [12]. Currently, mixed and two-fluids 3, 4 and 5 equations flow models are supported. For instance, 3 equations are used for the homogeneous single-phase flow pipe model, 4 equations for the drum model, and 5 equations for the separated flow pipe model. The different flow regimes are accounted for by appropriate pressure drop and heat transfer correlations. The drift-flux model may be used to compute the phase velocities. Also, accurate sets of geometrical data are provided for some heat exchangers.

Flow reversal is supported in the approximation of convective flow only (the so-called upwind scheme where the Peclet number is supposed to be infinite [13]). It is planned to investigate the interest of taking diffusion into account for a more robust computation of flow reversal near zero-flow.

The library components are written in such a way that there are no hidden or unphysical equations, that components are independent from each other and to ensure as much as possible upward and downward compatibility across tools and library versions. This is particularly important in order to control the impact of component, library or tool modifications on the existing models.

To that end, only the strictly needed constructs of the Modelica language are used. In particular, the inheritance and stream mechanisms are not used, and no physical meaning is assigned to the fluid connectors: they are considered as a mean to pass information between components, so they are not part of the physical equations.

The components are connected together using the fluid connectors according to the staggered grid scheme [4]. This scheme divides the components into two groups: volumes and flow models. Volumes compute the mass and energy balance equations, whereas flow models compute the momentum balance equations. Volumes may have any number of connectors, whereas flow models have exactly two connectors (they look like pipes, although they are not necessarily pipes). The staggered grid scheme states that flow models should be connected to volumes only, and volumes should be connected to flow models only. It is however possible to connect flow models together without breaking the staggered grid rule, by considering that the intermediate volume has a zero-volume capacity.

2.2. Organization of the ThermoSysPro library

The library is subdivided into application domains as shown in Figure 1. Each application domain corresponds to a type of connector and is itself subdivided into packages corresponding to main component families.

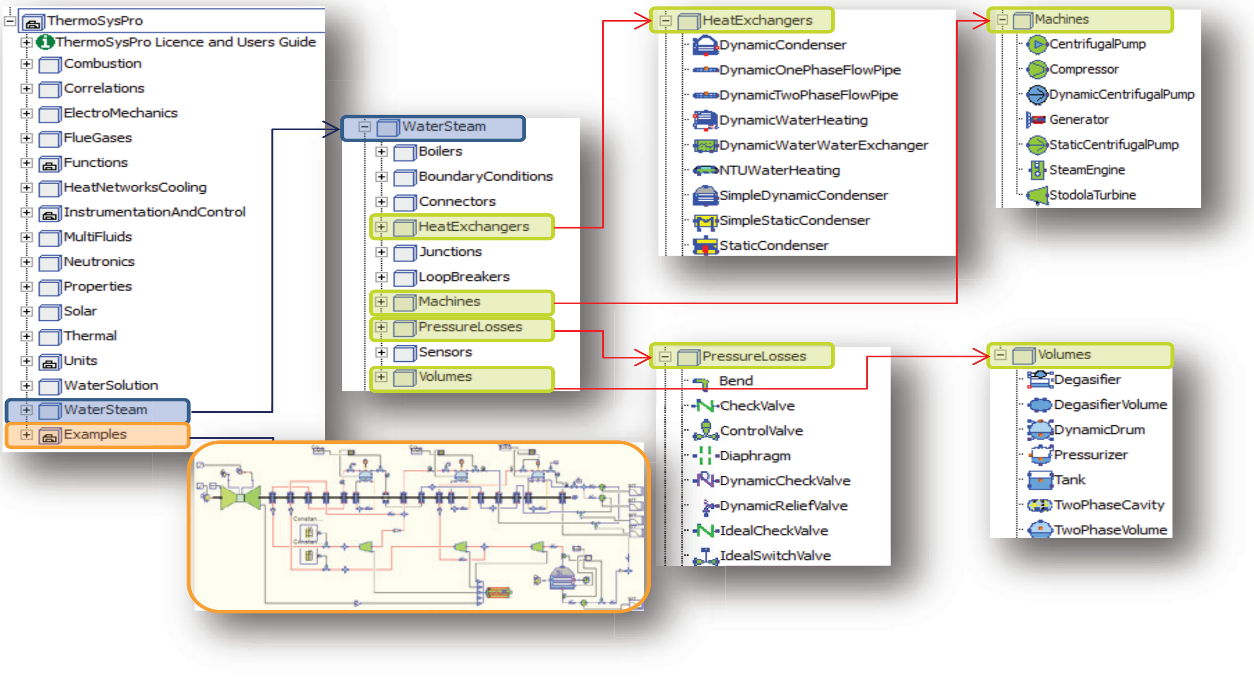

Fig. 1. Organization of the ThermoSysPro library

3. General presentation of the Central Receiver System

A molten-salt central receiver power system uses a tubular-type receiver mounted on top of a tower. Reflected solar energy from a field of heliostats heats the receiver; molten salt is the heat-transfer fluid, and it also cools the receiver. Figure 2 shows a flow schematic of this system. The molten salt used in this system is a mixture of 60 wt% sodium nitrate ($NaNO_3$) and 40 wt% potassium nitrate (KNO_3). It is heated from 290 °C to 565 °C in the receiver and then flows in pipes to thermal storage. Hot salt is extracted from the storage system to generate steam within a molten-salt steam generator. The steam feeds a Rankine-cycle turbine to produce electricity. The cooled salt is returned through the thermal storage system to the receiver. The thermal storage system buffers the steam generator from solar transients and supplies energy during periods of no sunshine, at night or on partly cloudy days. The hot-salt temperature of 565 °C enables steam production at temperatures and pressures typical of those used in conventional subcritical Rankine plants. To assure that the salt does not solidify (solidification point near 220 °C); each subsystem containing salt must be heated or drained.

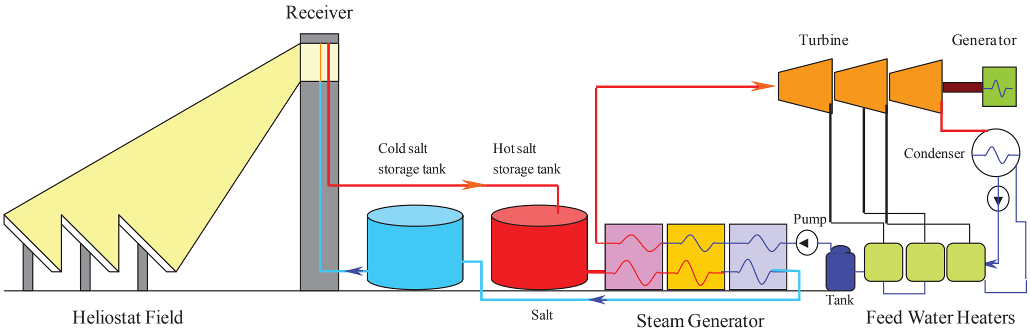

Fig. 2. Diagram of a Central Receiver System

4. Dynamic model of a Central Receiver System

A dynamic multi-configuration model of a Central Receiver System (CRS) solar power plant has been developed. The component model is meant to be used for power plant modeling with the ThermoSysPro library developed by EDF and released under open source license. The model is based on momentum and mass/energy conservation equations, as 1-dimensionnal (1D), partial differential equations. The primary aim of this study was to demonstrate the capability of said model to simulate the operating conditions of a solar power plant, and then the capability of the model to check the manufacturers design and targeted performances.

In order to be able to answer to many different situations, we created some variables in some of the component model enabling to switch itself **on** or **off**. So (*turbine stage, water heater, …)*, the same model can simulate several different plant configurations. This model (Modelica model translates with Dymola) includes all typical configurations, thus enabling its use through a user-friendly **Excel interface**. With this interface, comparisons between various architectures according to given criteria and constraints are easy, thus helping the user to define the best design. This interface can be used by a non-specialist in modeling.

4.1. Description of model

The model includes a solar receiver, storage tanks, steam generation system, steam turbines, feed water heaters, aerocondenser, several pumps, several valves, several component modeling pressure drops, several mixers, several collectors, generator, several sources, and several sinks:

Solar Receiver

This component receives energy from the heliostat field that concentrates solar radiation in different aiming points to avoid large spatial temperature gradients that could damage the component.

The model consists of several pipes heat exchangers (1D) in parallel, Figure 3. The model of the fluid flow in a cylindrical pipe is based on the dynamic mass, energy, and momentum balance equations, which are originally given as 1-D, partial differential equations. For the discretization of the model, the finite-volume method has been used. This is the model of the system in which the strongest simplifications have been made, due to the internal design of the system. **Therefore, a mean solar concentrated input power is used by mesh.**

The convection and radiation energy loss to the environment are modelled; the radiation and convection are modelled using the Stefan-Boltzmann Law and Newton Cooling Law.

Storage Tanks

The aim of the storage tank is to accumulate energy to let the plant operate when irradiation decreases during a time interval. The dynamic model of the tank is based on first principles mass and energy balance equations, Figure 3. The temperature of molten salt in the hot tank up to 565ºC with a capacity of 8 hours of electricity production without sunlight and the temperature of molten salt in the cold tank about 290 °C.

The storage model also considers heat losses of the cold and hot storage tanks.

Steam Generation System

Each heat exchanger model is divided into sub-models of three different types which are connected together to make the full model:

- Two Dynamic One Phase or Two Phase Flow Pipe model (1D),
- One Dynamic Heat Exchanger Wall model (1D),

The model simulates the thermal exchange between the salt and the water/steam. The model (two phases model for water/steam) is based on the dynamic mass, energy, and momentum conservation equations (homogeneous fluid), which are given as 1-dimensional, partial differential equations, the following phenomena are represented: transverse heat transfer, mass accumulation, thermal inertia, gravity and pressure drop within local flow rate. The Exchanger model contains precise and up-to-date correlations for the heat exchanger coefficients and pressure losses, for any phase (liquid, vapour or two-phase flow).

The Steam Generation System consists of five dynamics heat exchangers: Salt/ Water Steam (1 evaporators, 2 economizers, 2 super-heaters).

Steam turbine: Based on an ellipse law (Stoidola's law) and an isentropic efficiency [14].

Feed Water Heaters

The feed water heaters are heat exchangers that condense steam extracted from the turbine to heat feed water before it enters the economizer, thereby increasing the Rankine cycle efficiency. A feed water heater is a two-phase shell-and-tube heat exchanger. The feed water flows inside the tube bundle, while the steam and condensate flows outside of those tubes located inside the cavity. In the water heater, there are three distinct areas: (1) the desuperheating zone, (2) the condensation zone, both located in the upper part of the component, and (3) the subcooled zone, located in the lower part of the component. In some water heaters, the condensate of the water heater located upstream from the current water heater is re-injected into the current water heater. During re-injection, part of the condensate may vaporize due to the pressure drop (this phenomenon is known as flash). The level of the condensate in the cavity is adjusted with a valve located at outlet of the water heater. Each water heater model is divided into sub-models of three different types which are connected together to make the full model:

- Three Dynamic One Phase Flow Pipe model (1D)
- Three Heat Exchanger Wall model
- One Dynamic Two Phase Cavity model [8]
- Three Volume models

Aerocondenser: Based on first principles mass and energy balance equations for water/steam and air.
Steam exiting the turbine is condensed so that it can be pumped through the steam generation system.

Pump: Based on the characteristics curves.

Pressure drop in pipes: Proportional to the dynamic pressure ± the static pressure.

Mixer/splitter: Based on the mass and energy balances for the fluid.

4.2. The thermodynamic properties

Properties of salt: The thermo-physical properties of the salt were computed using polynomials equations.

Properties of water and steam: The properties for water and steam were computed from polynomials defined by the international standard IAPWS-IF97.

4.3. Modelica model

A dynamic Multi – configuration model in Modelica was developed to simulate the dynamic phenomena of the power plant. The full model is built by connecting the component models in a technological way.

In order to be able to answer to many different designs, we created some variables in several components of the model enabling to switch itself on or off. The same model can simulate different plant configurations:

- Switch on or off one turbine stage
- Switch on or off one water heating
- Switch on or off one economizer

This multi configurations dynamic model contains 828 elementary models, generating 11798 variables, 2811 equations, and 1826 non-trivial equations.

An important feature of this model is that the thermodynamic cycle is completely closed through the condenser.

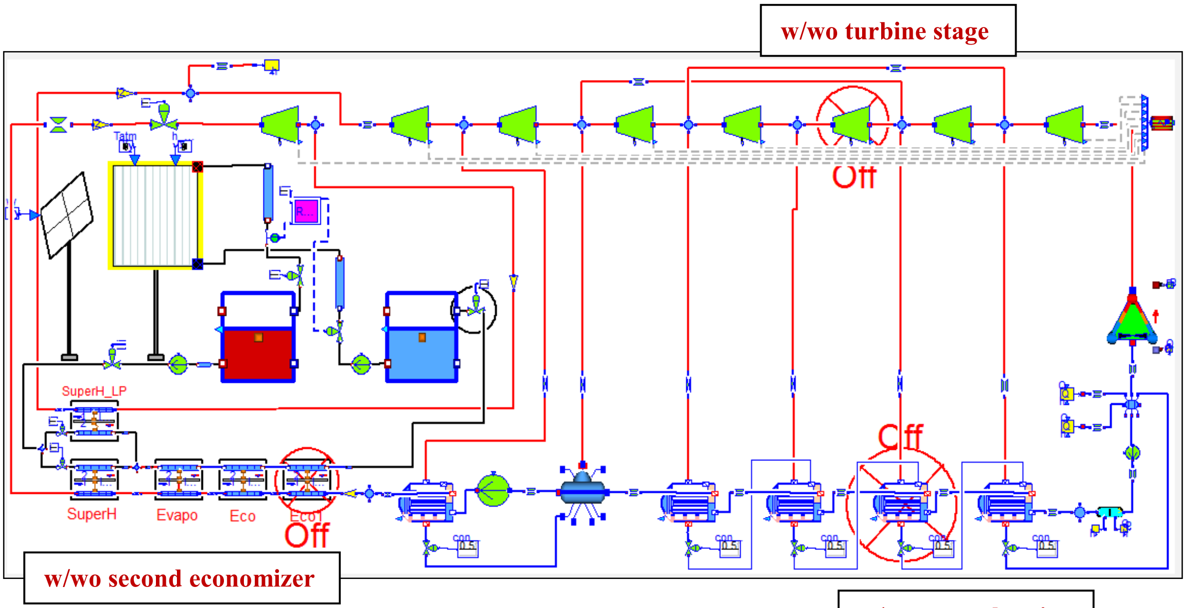

Fig. 3. Central Receiver System Modelica model

4.4. Calibration of the model

The calibration phase consists in setting (blocking) the maximum number of thermodynamic variables to known values. This method ensures that all needed performance parameters, size characteristics and input data can be computed by model inversion. A preliminary calibration of the model was made, the main computed performance parameters are:

- The ellipse law coefficients of the turbines
- Heat exchange surface the heat exchangers
- Lengths of pipes and exchangers
- Heat exchange surfaces of the aerocondenser
- Cvmax of the valves
- Characteristics of the pumps

4.5. Simulation scenarios and results

The dynamic model is capable of simulating the dynamic behavior of the entire Concentrated Solar Plant (CSP), several scenarios have been simulated:

The first scenario:

With three compounds switch off (one turbine stage, one water heater and one economizer): The simulation scenario represents the variation of the solar energy during one day (with solar irradiation "DNI" as only operation) from 0 W/m² to 920 W/m² (see Figure 5) and maintain constant the mass flow of the hot molten salt to maintain the power produced by the CSP is constant during some time.

The dynamic performance of the model is evaluated by supervising the evolution of key variables such as the fluid temperature, fluid mass flow rate, fluid pressure and electric power generation.

The simulation runs were done using the Dymola software version 6.1 and 2014, with Dassl solver. The results of the simulation are given in Figure 4 and 5. The model converges very quickly, provided that the iteration variables (approx. 5 % of the total number of variables) are properly fed in by the user (70s cpu for simulate 70000s.)

The results of the first scenario are shown in figure 4. The first graph presents the evolution of DNI in each time interval (20h of weather conditions, from 07h00 AM to 03h00 AM), the second graph presents the mass flow of the molten salt to the steam generation system, the third graph presents the water/steam temperature at the outlet of the HP super-heater and the molten salt temperature at the input of the steam generation, the fourth graph presents the power produced by the concentrated solar power plant , the fifth graph presents the load/unload cycle of the cold tank and the last graph shows the load/unload cycle of the hot tank.

The results of the simulation in the last graph of Figure 5 shows:

1. Initial state: the hot tank is unloaded
2. from time = 0s to 1000s, the power from the heliostat field is zero and all the energy delivered to the steam generation comes from the storage tank (tank level decreased)
3. At time = 11900s, the storage tank begins to accumulate energy (tank level increased)
4. At time = 45080s, the storage tank finished to accumulate energy (maximal level = 17.15 m)
5. At time = 54000s, the power from the heliostat field is zero and all the energy delivered to the steam generation comes from the storage tank (tank level decreased to 0.53 m)
6. The capacity of storage of salt, allows us to maintain the power produced by the CRS constant during 20h from 07h00 AM to 03h00 AM

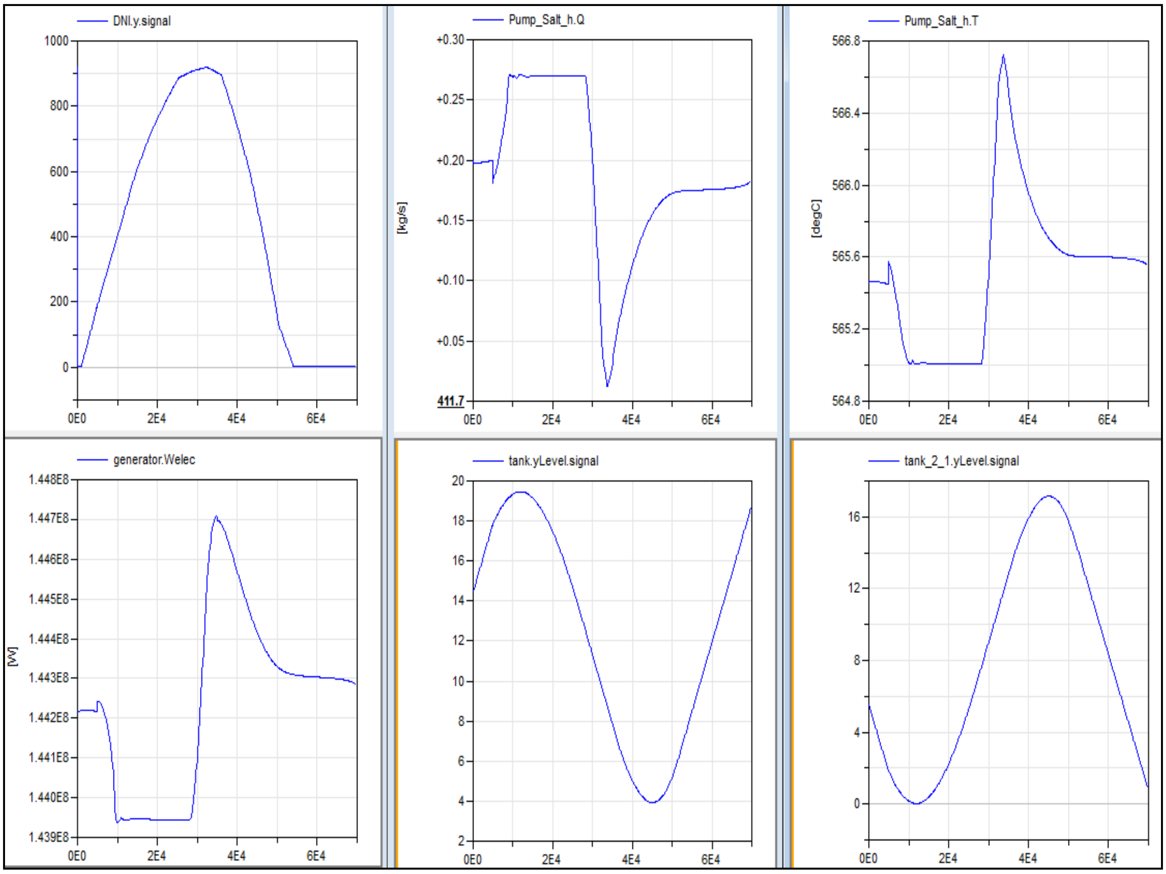

Fig. 4. Evolution of DNI, mass flow rate of the salt at the input of the steam generation, salt temperature at the input of the steam generation, the produced electric power, the load/unload cycle of the cold tank and the load/unload cycle of the hot tank.

<u>The second scenario:</u>

With two compounds switch off (one turbine stage, one water heater) and with economizer switch on. The heat exchange surface of the second economizer is equal 25 % of the first heat exchange surface (first economizer). The results of the first scenario are shown in figure 5.

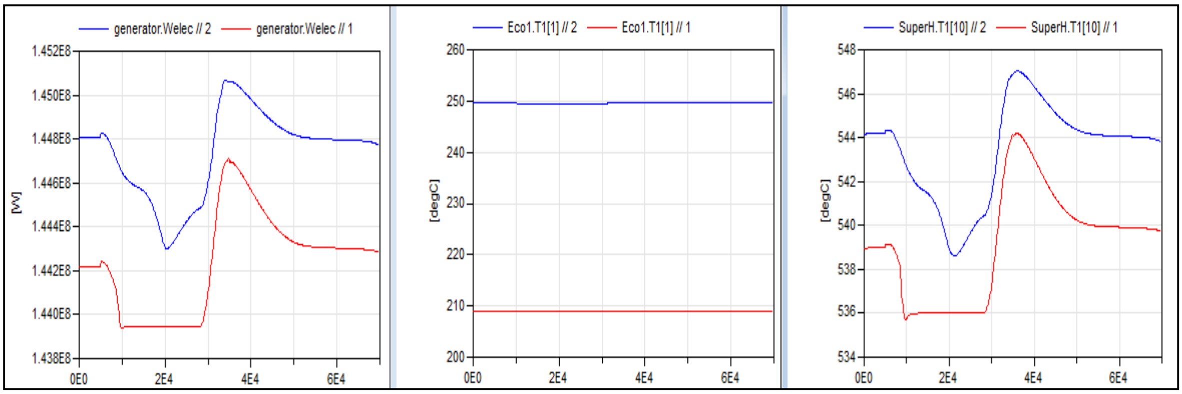

Fig. 5. Evolution of the produced electric power, temperature at the outlet of the second economizer and temperature at the outlet of the HP super-heater (**bleu** curve for economizer **on** and **red** curve for economizer **off**)

4.6. Tool for non-modeller

The executable file of the model can be integrated in an easy-to-use Excel sheet or in the ATOS tool (see Figure 6) for non-modelers, and it may be given to our customer. With this tool (ATOS) and the Modelica model, the user can make calculations on any plant configuration with varying DNI.

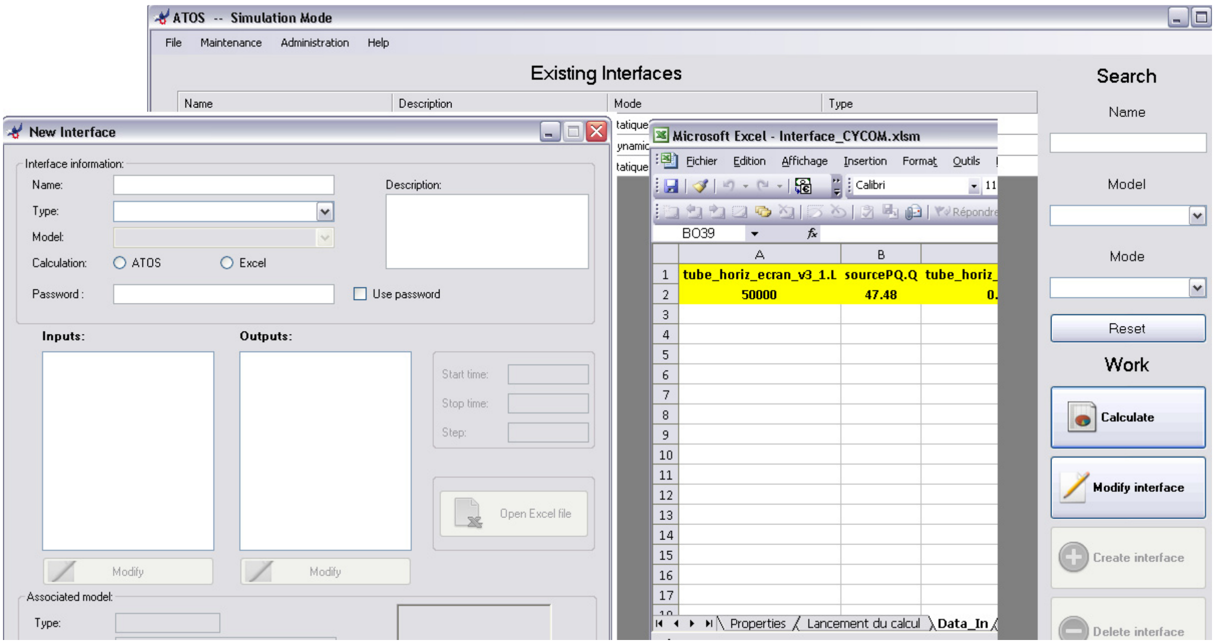

Fig. 6. The ATOS interface and Excel interface

5. Future work

- Develop of the control system of the plant
- Adjusting of the main block models parameters based in the experimental results of the real plant,
- Simulation of the start-up and shutdowns of the plant

6. Conclusion

This article shows the development of a dynamic multi-configuration model of a CRS, using the ThermoSysPro library developed by EDF. This library has been mainly designed for the static and dynamic modeling of power plants, but can also be used for other energy systems such as industrial processes, buildings, solar, etc.

The present paper focuses on the load/unload cycle of the storage tank, an scenario with a typical operation cycle and real DNI has been simulated. The results are shown for a day sunny (DNI) with solar-only operation, the capacity of storage of salt, allows us to maintain the power produced by the CRS constant (145 MW) during 20h from 07h00 AM to 03h00 AM.

The models also allow us:

- To check precisely the performances and the design (sizing of the components) given by the manufacturers
- To verify and validate by simulation the scenario of large transients
- To reduce the uncertainty on the yearly electricity production (simulation with yearly DNI)

References

[1] Bouskela D., Chip V., El Hefni B., Favennec J.M., Midou M. and Ninet J. ‘New method to assess tube support plate clogging phenomena in steam generators of nuclear power plants’, Mathematical and Computer Modelling of Dynamical Systems, 16: 3, 257-267, 2010

[2] El Hefni B., Bouskela D., ‘Modelling of a water/steam cycle of the combined cycle power plant “Rio Bravo 2” with Modelica’, Modelica 2006 conference proceedings.

[3] El Hefni B., Péchiné B., ‘Model driven optimization of biomass CHP plant design’, Mathmod conference 2009, Vienna, Austria.

[4] El Hefni B. ‘Dynamic modeling of concentrated solar power plants with the ThermoSysPro Library’ (Parabolic Trough collectors, Fresnel reflector and Solar-Hybrid, SolarPaces 2013, Elsevier’s Energy Procedia.

[5] David F., Souyri A., Marchais G., ‘Modelling Steam Generators for Sodium Fast Reactors with Modelica’, Modelica 2009 conference proceedings.

[6] Souyri A., Bouskela D., ‘Pressurized Water Reactor Modelling with Modelica’, Modelica 2006 conference proceedings.

[7] El Hefni B., Bouskela D., ‘Dynamic modelling of a combined cycle power plant with ThermoSysPro’, Modelica 2011 conference proceedings

[8] Baligh El Hefni, , Daniel Bouskela, Guillaume Gentilini ‘Dynamic modelling of a water heater with the ThermoSysPro Library’ Modelica2012

[9] L.J. Yebra, M. Berenguel, S. Dormido, M. Romero ‘Modelling and Simulation of Central Receiver Solar Thermal Power Plants’, Modelica 2005.

[10] S. Rodat, J.V.D. Souza, S. Thebault, V. Vuillerme, N. ‘Dupassieux Dynamic simulations of Fresnel solar power plants’ SolarPACES 2013, Elsevier’s Energy Procedia.

[11] L.J. Yebra, M. Berenguel, S. Dormido, M. Romero ‘Modelling and Simulation of Central Receiver Solar Thermal Power Plants’, Modelica 2005.

[12] Collier J.G., and Thome J.R., ‘Convective Boiling and Condensation’, Mc Graw-Hill Book Company (UK) limited, 1972 Clarendon Press, Oxford, 1996.

[13] Patankar S.V., ‘Numerical Heat Transfer and Fluid Flow’, Hemisphere Publishing Corporation, Taylor & Francis, 1980.

[14] Bidard R., Bonnin J. Energétique et turbomachines « Eyrolles/Paris », 1979.